Effect of a Deposited Coupling Loop on the High-Speed Switching Properties of a Magnetic Thin Film

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Summary: Future applications of magnetic thin films to computer circuitry will require the use of integrated deposited circuitry, which involves depositing magnetic films and associated electrical circuitry on the same substrate. It is verified that the extremely close coupling between a magnetic film and a surrounding deposited loop in this configuration results in 100% flux linkage with the loop. The dependence of the observed flux linkage of the deposited loop on the loop circuitry is studied; the effect of width, thickness, and separation of deposited loop conductors on high-speed film switching is investigated; and the relative importance of circulating loop currents and eddy currents in the conductor materials in slowing film switching is evaluated.

UP TO THE PRESENT, most applications of magnetic thin films to computer memory and logic devices have used magnetic film elements deposited on some substrate material and then coupled relatively loosely to the appropriate circuitry by overlaid wires or or strip conductors.[1–3] To realize the full potential of thin films, future developments in this field will involve integrated deposited circuitry, i.e., the deposition of the magnetic films and associated electrical circuitry on the same substrate.[4] Such structures will require a better understanding of the behavior of a magnetic film when it is very closely coupled to conducting loops and other adjacent deposited conductors.

The simplest configuration for such an arrangement is a single magnetic film element that is closely coupled to, but insulated from, a single deposited conducting loop surrounding the element. By observing the effect of the presence of this loop on the high-speed transverse switching response of the film, the importance of loop coupling can be evaluated.

The flux linkage of the deposited loop and the variation of film output waveforms and switching times with such loop parameters as conductor width, thickness, and separation were determined experimentally. With certain configurations, the presence of the loop was found to slow significantly the switching of the film. This decrease in switching speed indicates that integrated deposited circuitry may not be capable of attaining such high operating speeds as might be inferred from the switching of an isolated magnetic film.

Mechanisms Affecting Observed Switching Response of a Coupled-Loop Magnetic Film

The interaction between a switching magnetic thin film and a closely coupled conducting loop arises from two sources, circulating currents in the loop conductor and eddy currents in the conducting loop material. The magnetic fields, produced by these currents, modify the film switch-

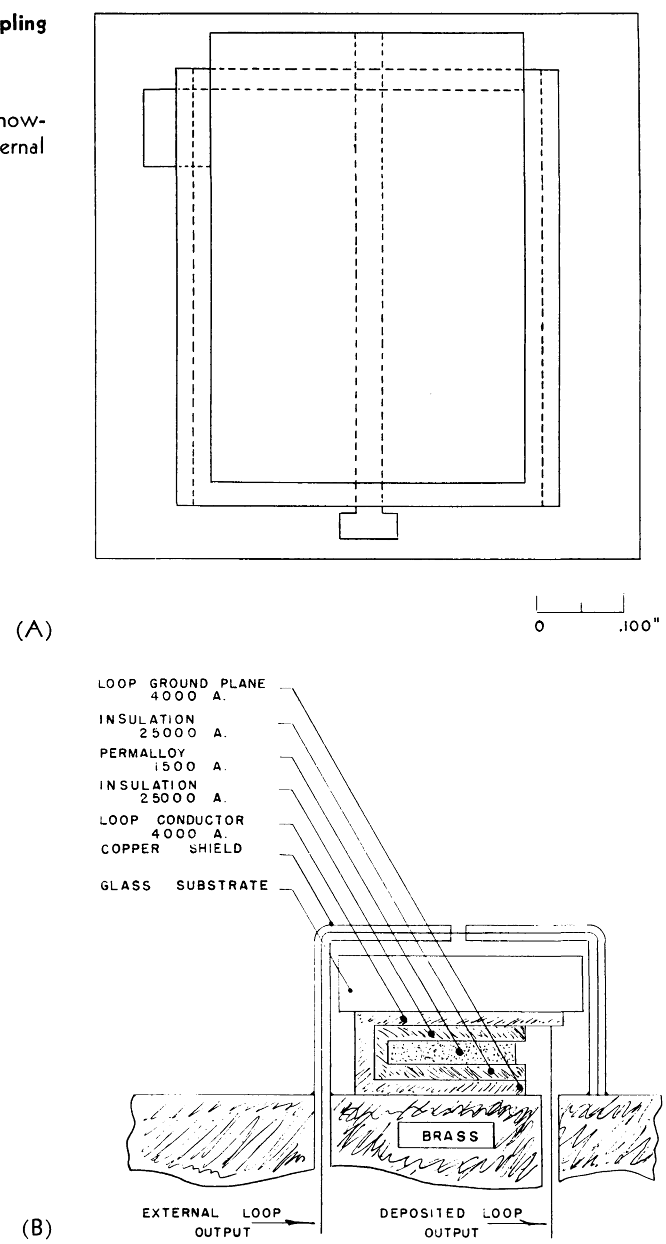

Fig. 1. Film and coupling loop assembly

A—Plan view
B—Sectional elevation showing deposited and external loop circuitry

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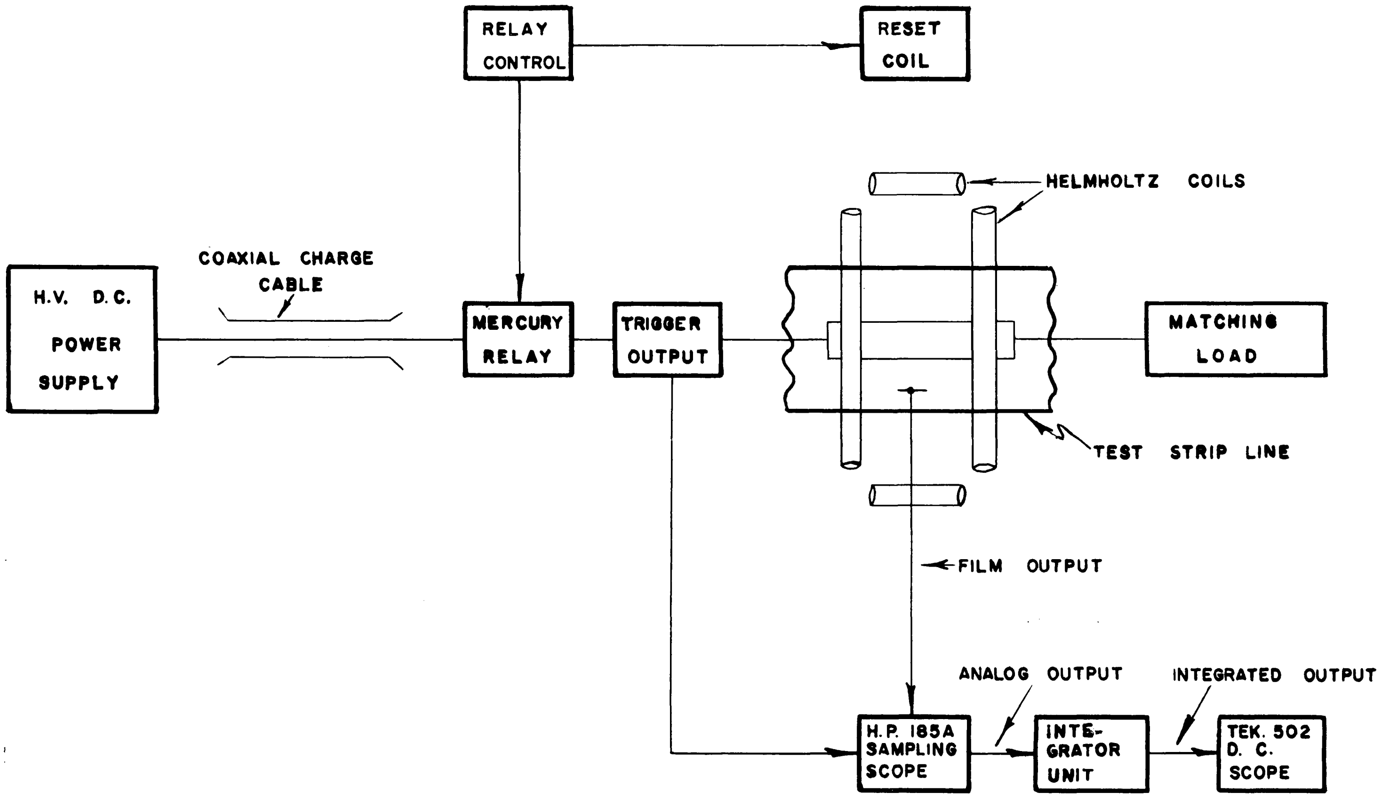


Fig. 2. High-speed film switching test equipment

ing. Since the film-loop coupling is very tight, this modification occurs only in the portion of the film covered by the loop. When the magnetizations in the two regions begin to switch differently, a demagnetizing interaction occurs which tends to preserve the alignment of the two magnetization vectors. The effect of the coupling loop on the total film is dependent, therefore, on the width of the loop relation to the film width. Io addition to these factors, which determine the switching response of the magnetic film itself, the output of any loop surrounding the film is dependent on the loop transfer function which modifies the induced voltage in that loop.

Film Fabrication

The magnetic film aad coupling loop assemblies were made four at a time by vacuum deposition. Using glass substrates heated to 300 C (degrees centigrade), deposition of the five layers [Permalloy (83% nickel–17% iron), aluminum (conductor material), and silicon monoxide (insulator material)] was effected without opening the vacuum in the system. A plan and sectional elevation of a complete film assembly are shown in Fig. 1. The dimensions shown in the plan view are exact, while those on the elevation are nominal, varying with the deposition and the test requirements of the completed assembly.

Static measurements were made on each film before it was accepted for high-speed switching experiments. It was required that the static **B-H** loops along both the hard and easy axes be similar to those for the other films of the set. Deposited loop resistance was recorded with acceptable values in the range of 1–10 ohms. The insulation resistance between the Permalloy and loop was determined; in many cases, where the resistance between the two conductors was less than 1 kilohm, caused by pinholes in the silicon monoxide layers, the resistance could be increased to an acceptable value of 10 kilohms by applying about 20 volts across the insulation.

Test Equipment

A block diagram of the high-speed film switching test equipment is shown in Fig. 2. It uses the conventional high-voltage d-c supply, charge cable, and mercury relay system for the generation of the fast-rise magnetic field in the test strip line.[5] Using a maximum charging voltage of 5 kv, a drive field of 6.5 oersteds is obtained in the test region of the strip line. The duration of this field, having a rise time of about 1 nsec (nanosecond), is about 500 nsec, as determined by the length of the charge cable. The repetition rate of the field is 60 pps (pulses per second), with the mercury relay being driven synchronously from the utility line. The two loops, deposited and external, are arranged as shown in Fig. 1(B). The spring-mounted deposited loop probe, consisting of a ceramic covered copper wire, presses against the end tab of the deposited loop conductor, while the ground plane of the loop is held in contact with the strip-line ground plane by clamping the substrate into position. The external loop, made of enamel-insulated copper wire, is electrostatically shielded to minimize pickup from the drive field. In all tests, the magnetic drive field is applied perpendicular to the loop axes, so no air-flux compensation loop is required for the external loop.

The output of either loop displayed on the sampling oscilloscope may also be integrated with respect to time by using the integrator compensator unit, which compensates somewhat for drift in the analog output of the sampling oscilloscope. The frequency response of the measuring system is limited only by the 0.8-nsec rise time of the sampling oscilloscope circuitry, since the analog signal is slow compared to the response time of the operational amplifiers used in the compensator unit.

Measurement of noise and pickup in both loops was readily made by applying a steady magnetic field of about 100 oersteds in the plane of the film to block any response of the film to the drive field; for films thicker than 1,000 A (Angstrom units), these extraneous signals were usually negligible.

Switching Experiments

In all the experiments, the magnetic drive field was applied along the hard axis of the film, with the reset field applied between pulses to set the magnetization in one direction along the easy axis. When the drive field exceeds the anisotropy field H_k, the final position of the film magnetization with the drive field still present is assumed to be along the hard axis.

The deposited loop is coupled very closely to the film so that all of the flux links this loop. However, appreciable flux closure is expected within the external loop so that the integrated external loop signal should be smaller. By assuming that the magnetization, when directed along the easy axis, is represented by two uniform magnetic line charges along the edges of the film at both ends of the easy axis, the expected ratio of flux linkages can be calculated to be 0.777 for the particular external loop used here. The effect of the loop resistance is accounted for by considering the loop circuitry as a linear passive lumped-parameter 2-port network. The ratio of the output voltage V_2 to the input voltage V_1 is expressed, in Laplace transform notation, in the following form:

$$\frac{\bar{V}_2(s)}{\bar{V}_1(s)}=\frac{P(s)}{Q(s)} \qquad (1)$$

where $\bar{V}_2(s)$ is the transformed output voltage, $\bar{V}_1(s)$ is the transformed input voltage, and $P(s)$ and $Q(s)$ are polynomial functions of the variable s. If it is assumed that all the time derivatives of V_2 and V_1 exist and that the values of the voltages and all their time derivatives vanish at initial and final time, equation 1 yields

$$\left[1+C_1\frac{d}{dt}+C_2\frac{d}{dt^2}+\ldots\right]V_2$$
$$=\frac{P(0)}{Q(0)}\left[1+K_1\frac{d}{dt}+K_2\frac{d^2}{dt^2}+\ldots\right]V_1 \quad (2)$$

where C_1, C_2, ..., K_1, K_2, ..., are constants.

Integrating equation 2 with respect to time between the limits $t=0$ and $t=\infty$ gives

$$\int_0^\infty V_2dt=\frac{P(0)}{Q(0)}\int_0^\infty V_1dt \qquad (3)$$

Thus, the ratio of flux observed to flux linking the loop depends only on the direct voltage transfer ratio for the loop and its termination; by using the resistance values for the deposited and external loops, the variations of integrated signal ratio with deposited loop resistance can be calculated.

The integrated signal ratio was determined as a function of the loop resistance for a number of films having a constant width loop covering one-twelfth of the film width. A drive field of about twice H_k was used. The results are plotted in Fig. 3, where the experimental points are seen to be in good agreement with the theoretical curve as given by the solid line.

The effect of the coupling loop on the magnetic film is to produce slower switching for the same drive. A set of films, each having a ground plane conductor, was deposited with the following loop conductor variation (all loops are the full width of the film and are the same thickness): film A has no loop conductor; film B has a loop conductor which is not connected to the ground plane conductor; film C has a loop conductor connected to the ground plane conductor at one end; and film D has a loop conductor connected to the ground plane conductor at both ends.

The waveforms obtained in the external loop with a drive field of about twice H_k are shown in Fig. 4. Films A and B showed no significant difference in output waveform. The signal of film C was slowed quite appreciably, while that of film D was found to be affected still further.

The similarity of signals A and B indicates that the effect of eddy currents on film switching is negligible for the conductors used. Slowing of the output signal in film C indicates that switching is affected significantly by the circulating currents in the loop which is completed by the capacitance between the loop conductor and its ground plane; this capacitance is approximately 1,000 pp (picofarads). A field of 10 oersteds (nearly 3 H_k) can be expected from the circulating currents, assuming negligible loop resistance, 1-nsec switching, and a rate of voltage rise of 6 volts/nsec, which is fairly representative of the nominal film and loop assembly. This field, directed along the film easy axis, will clearly slow the film switching. The loop impedance is decreased when the loop is short circuited (film D). The observed decrease in switching speed is caused by the larger currents which result from this decreased impedance.

The results of the last experiment allow the effect of conductor separation and thickness on the output of the magnetic film to be predicted. Since the circulating current from loop capacitance was shown to provide large fields in the film region, an increase of conductor separation should be accompanied by an increase of film switching speed. Accordingly, a set of films was made with loop insulation layer thicknesses of 10,000, 20,000, 30,000, and 40,000 A. Each deposited loop covered half the width of the film. A 30% decrease in film switching time occurred with increased insulation thickness, because of the decreased capacitive loading of the loop. By contrast, the thickness of the loop conductor material should produce no appreciable effect on the switching of the film since the main loop parameter varied is the eddy current field of the loop. This conclusion was verified by switching experiments on a set of films with conductor thicknesses of 2,500, 5,000, 7,500, and 10,000 A.

The magnitude of the effect of the circulating loop current on the film switch-

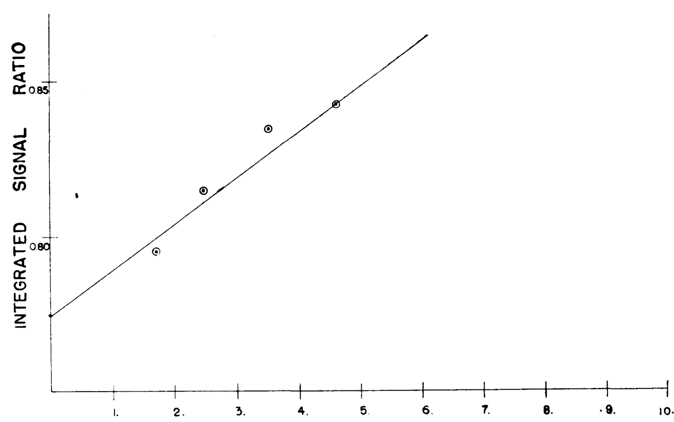
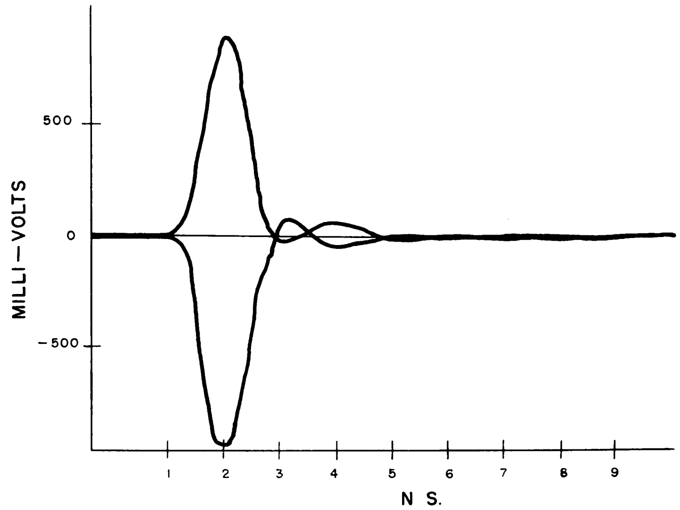
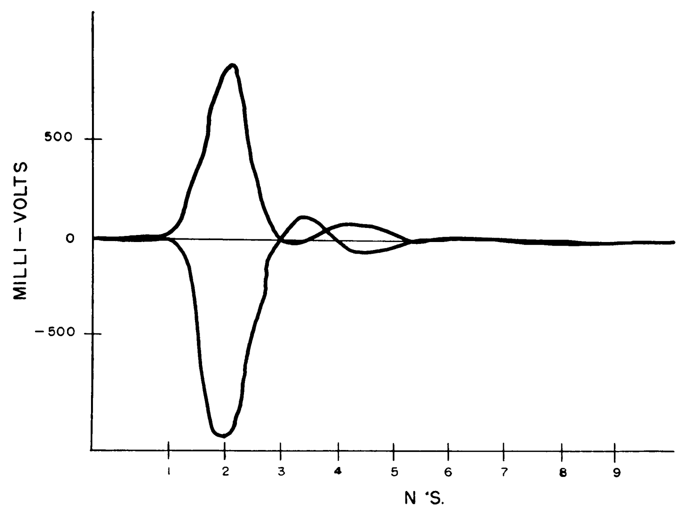


Fig. 3. Variation of integrated signal ratio with deposited loop resistance

Fig. 4. Switching voltage waveforms showing signal obtained with the reset field directed along both directions of the film easy axis; the center line in all oscillograms is the pickup in the external loop



Film A



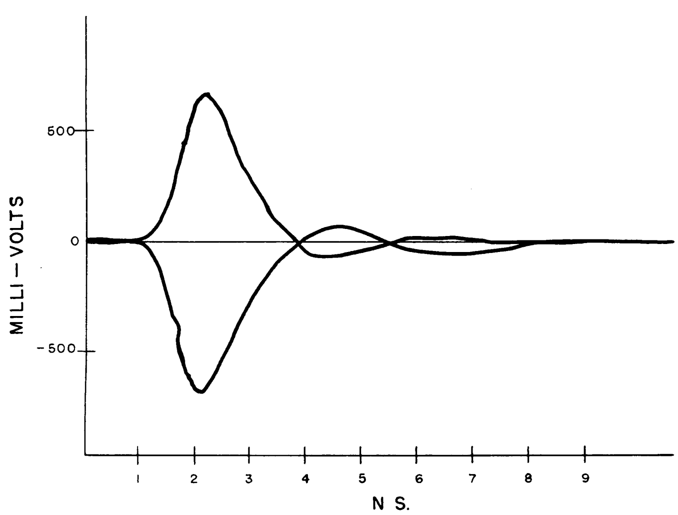
Film B

ing depends on the proportion of the film covered by the loop. Changing the conductor widths from 8% to 100% of the width of the film showed a very marked decrease in switching speed with increased conductor width. The inverse switching times versus magnetic drive field for three films of this set are shown in Fig. 5. The switching time τ is defined as the time interval from 10% to 90% of the total flux change. For drive fields less than H_k, τ is corrected by the ratio of switched flux to total film flux. A further decrease in the switching speed of film 3, as observed on the external loop, when the deposited loop is short circuited by some silver conductive paint, is attributable to the increased loading of the deposited loop.

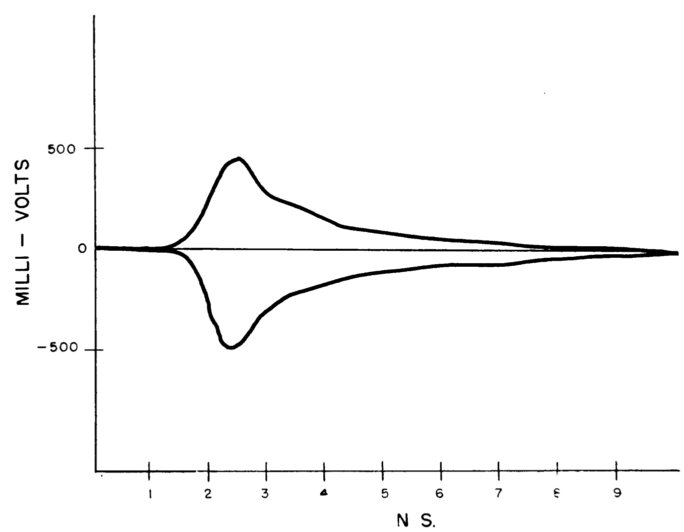
The switching curve of film 1, which has the narrowest loop, may be assumed to be fairly close to the characteristic for a film, with no loop coupling it. It is seen that a 100%-width loop increases the switching time by a factor of about 2.5.

Conclusions

Two important measurements to be made on the output of a magnetic film closely coupled by a deposited loop are the observed flux change and switching time of the film. It has been determined that the observed flux change can be quite accurately predicted on the basis of the d-c response of the measuring loop and of a simple static model for the magnetic film. The interaction between the film and the deposited coupling loop is caused by circulating currents in the loop circuitry. The effect of eddy currents in



Film C



Film D

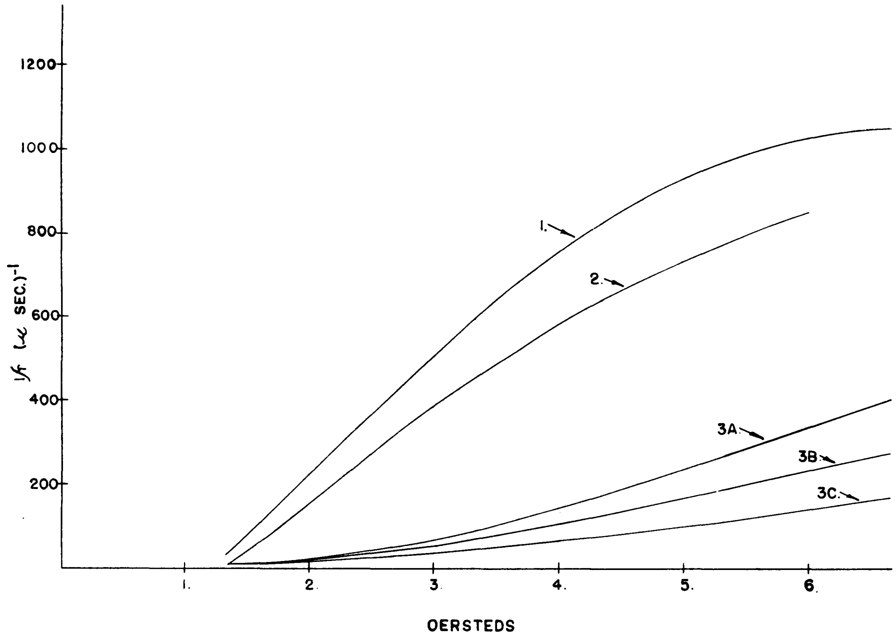


Fig. 5. Switching films for films 1, 2, and 3. Curves 1, 2, and 3A are measured from the deposited loop output; curves 3B, and 3C are measured from the external loop output

the loop material is negligible for conductor thicknesses of the order of 10,000 A. Film switching is affected by the width and separation of the loop conductors, but is relatively independent of the thickness of the conductor material; loading of the loop, caused by external circuitry, also affects film switching significantly.

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Static Relaying Devices Using Magnetic Cores and Silicon-Controlled Rectifiers

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THE BASIC PURPOSES of the relays associated with a power transmission system are: to detect any fault within the system, to localize the fault distinctly to a particular section of the system, and to cause that section to be disconnected without interfering with continued supply to the remainder of the system.[1,2] In order to appreciate the relaying problem, the two familiar types of power system structure shown in Fig. 1 should be examined. In a radial system, a load fault can often be detected simply from the existence of an overcurrent; however, if the load contains transformers with high inrush currents on excitation or motors with high starting currents, it may be desirable to delay tripping the breaker, either by a finite time or by a time inversely dependent on the current. If a fault occurs in line section *C-D* of Fig. 1, all line relays will indicate an excessive current. But, since only the breaker in line *C-D* should operate, service to the other loads may be maintained. Thus, it is necessary to delay operation of the breaker in line *B-C* until the breaker in line *C-D* has had sufficient time to open, and provision must be made for the time-current co-ordination of the line relays.

The mesh system of Fig. 1 is arranged so that each load may receive its supply from either or both of two lines. In this system, the existence of an overcurrent at one relay location does not provide information on the location of the fault. In general, it is necessary to compare the currents entering and leaving a line section to determine whether the fault exists within that section. This comparison involves a communication channel.

In both the radial and the mesh system, it is desirable to provide backup protection. If any circuit breaker fails to open properly after a fault, the relays in neighboring line sections should detect the faulted condition and disconnect the faulty section.

At present, most of the relays used in the protection of transmission and distribution systems are electromechanical in nature; among the widely used types are the instantaneous relay, the inverse-time relay, the impedance relay, the differential relay, and the phase-comparison relay. These electromechanical relays suffer from the following disadvantages: relatively low reliability, mainly due to electrical contacts and friction in moving parts, necessity of regular maintenance, inaccurate timing which requires large safety margins in co-ordinated systems, relatively high power consumption, and limited flexibility in the protection functions provided.

This paper describes static relays which use rectangular-loop magnetic cores and silicon-controlled rectifiers (SCRs) to duplicate the functions of most electromechanical relays and to provide some functions not previously available. The relays described depend on the line current measured at one or both ends of the line; relays, such as the impedance type, which use information from both the current and voltage of the line are not considered.

Relays for Radial Systems

Instantaneous Overcurrent Relay

The instantaneous overcurrent relay operates within one cycle after the

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